LCAs for Waste

Life Cycle Assessments for Waste, Part II:

A Comparison of Thermal Treatment Processes for Hazardous Waste

Strategic EIA for the Dutch National Hazardous Waste Management Plan 1997-2007

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Preamble

This series of three articles titled "LCAs for Waste" describes the experience of performing comparative assertions of hazardous waste management technologies for the second Dutch National Hazardous Waste Management Plan (NHWMP) 1997-2007. For this plan, Dutch legislation required that a strategic (thus: chain-oriented) Environmental Impact Assessment (EIA) had to be made. The NHWMP, which was written in parallel, used the EIA's results directly to establish so-called 'minimum standards'.

These can best be described as a 'Best available technology' for management of certain hazardous wastes. Only such technologies would be licensed under the NHWMP.

The **first part** describes the Dutch hazardous waste management structure, and the goal and scope definition step for the chain-oriented EIA.

The **second part** presents a comparison of thermal treatment technologies.

The **third part** provides a comparison of paint packaging separation plants. Furthermore, it gives a general review of the usefulness of LCA for the NWHMP, its acceptance in the public consultation phase, and the experience with the review process by the Dutch EIA commission.

Abstract. This paper (the second in a series of three) compares incineration options for hazardous waste with LCA. Provided that acceptance criteria are met with regard to metals, PAHs and chlorine, Dutch Municipal Solid Waste Incinerators (MSWIs) appeared to be preferable above rotary kilns since they have a better energy recovery and – unlike rotary kilns – produce reusable slags. The position of the cement kiln relative to the MSWI and rotary kiln depends on the allocation method chosen. System enlargement, which may be most highly defensible, tends to give cement kilns the advantage. Yet, two key concerns which are unsolvable by LCA make final conclusions impossible. First, an input of highly contaminated waste leads to an enrichment of cement with metals. Long-term consequences are not known, so the incineration of waste with a high metal content will inevitably be controversial. Second, no convincing proof was found that cement kilns would not produce additional hazardous process emissions (e.g. dioxins) when using waste instead of fuel. The precautionary principle demands that such proof be provided before cement kilns can be considered for the incineration of waste with a composition other than their regular fuel.

Keywords: Dutch National Hazardous Waste Management Plan; EIA; Environmental Impact Assessment; hazardous waste; incineration; LCA; Life Cycle Assessment; thermal treatment; waste management; waste

1 Introduction

One of the most tense decisions to be taken in the Dutch National Hazardous Waste Management Plan (NHWMP) of 1997 was the choice of the reference technology (the so-called 'minimum standard') for thermal treatment (VROM/IPO, 1997). With landfill, thermal treatment is the cornerstone of any hazardous waste management system (→ *Fig. 1* in Part 1, p. 277). Dutch incinerable hazardous waste is currently treated with Municipal Solid Waste Incinerators (MSWIs), rotary kilns (both at AVR Chemie, near Rotterdam), and cement kilns (abroad; → *Table 1.1*)[1]. Policy makers had always seen cement kiln incineration as a 'second best' option, only allowed if AVR had no capacity[2]. However, cement kiln operators professionalised their services, and started a lobby to have cement kiln incineration accepted as a recycling/recovery operation for which EU regulations allow a free transboundary movement of waste. Not pleased with the AVR's monopoly, they got support of many Dutch firms in the hazardous waste chain. Furthermore, a major Dutch shipping waste treatment firm, which produced several dozen kilotons of incinerable residues, reacted by planning its own incinerator[3].

Table 1.1 reflects the importance of which technology the NHWMP would prefer. This choice could jeopardise AVR's de facto monopoly position, but also frustrate the cement kiln industry's intention to size a larger part of the waste incineration market. In this context, TNO started to make

[1] Due to capacity problems some incinerable hazardous waste was still landfilled in 1995.
[2] This made AVR-Chemie a de facto monopolist, reflected by the fact in the early nineties they made profits up to 30% a year.
[3] Later, AVR Chemie decided to buy this firm, a.o. in order to ensure continuity in waste supply.

Table 1.1: Dutch incinerable hazardous waste supply by technology in ktonnes. Actual data for 1995 and forecast for 2005 (TUKKER, 1997: 9)

Technology	1995	2005 (scenario a)	2005 (scenario b)
MSWI	60.8	61.2	59.3
Cement kiln	67.2	65.3	62.4
Rotary kiln	137.3	143.7	138.1
Landfill	12.6	-	-
Total	277.9	270.2	259.7

the LCAs that should underpin this preference, as a part of the Environmental Impact Assessment (EIA) on the NHWMP (cf. TUKKER, 1996a).

This paper summarises this work. For methodological aspects, we refer to **Part 1** (TUKKER, 1999). **Section 2** describes the technologies and the data inventory. **Section 3** describes the impact assessment and its result, and deals specifically with three major bottlenecks in the comparison: The allocation procedure, the final fate of heavy metals in incinerable waste, and the concerns about an additional formation of micropollutants. **Section 4** provides the overall conclusions.

2 Functional Unit, Relevant Technologies and Data Inventory

2.1 Functional unit and relevant technologies

As a functional unit, we chose the treatment of 1 tonne of incinerable waste with some typical compositions. As for the technologies, the introduction indicates that the following ones had to be included in any case:

- Rotary kilns;
- MSWIs;
- cement kilns;
- the kiln type proposed by the treatment firm of ship waste, a so-called combi-kiln[4].

Table 2.1: Acceptable aggregations of incinerable hazardous waste by incineration technology

Technology Aggregation	MSWI	Rotary kiln	Cement kiln	Combi-kiln[a]
High caloric, liquid		+	+	+
Low caloric, liquid	(+)	+	+	+
Sludge	+	+	+	+
Solid	+	+	+	
Packed		+		

[a] Also incinerates gaseous high-caloric waste, produced on location

[4] Other technologies like gasification and pyrolysis were not seen as mature enough to serve as a minimum standard for hazardous waste. However, an initiator proposing such technologies still can be granted a license if he proves that they are robust and are environmentally equally attractive as the minimum standard.

The kilns may have restrictions with regard to the aggregation of the waste input (→ *Table 2.1*). Also, certain acceptance limits for waste composition may apply. Hence, a kiln can only play a role in a comparison if the waste at stake meets such acceptance criteria.

In most cases, apart from the function 'waste destruction', these technologies fulfil other functions, such as 'electricity production' or 'heat generation', that differ for each technology. The following approaches can ensure that similar functional units are compared:

1. System enlargement or its analogue, avoided emissions. Allocation is in fact avoided by enlarging the system. If a system represented by one technology does not deliver all relevant functions, standard technologies (e.g. heat production with gas) are added to that system, ensuring that all functions are delivered after all;
2. functional allocation. By a division rule based on physical relations, physical values or economical values, the environmental interventions related to the system represented by the technology are allocated to each of the functions this technology delivers.

There is much debate as to which approach is the best. An advantage of system enlargement is that it gives insight in the total effect of decisions with regard to waste management technologies, including 'inductions' in other production chains[5]. The Dutch authorities like to have such insight about the (indirect) effects of their decisions. Hence, we used system enlargement as a default and functional allocation as sensitivity analysis where relevant[6].

Below, a description of these technologies, their related process chains, and the sources for the data inventory are given. In general, primary data was gathered for the central treatment processes. This data is reviewed in **Table 2.2**. For other (background and avoided) processes, data was taken from generic LCI-databases or other studies (e.g. AOO, 1995a, SAS, 1994, FRISCHKNECHT, 1994).

[5] For instance, the process-related emissions of a cement kiln in principle do not change when fuel is replaced by waste. Thus, if the cement is made anyway, the additional (process-related) emissions of using waste are zero. But with functional allocation, the cement kiln's new function 'waste destruction' would get allocated a part of these emissions - implying that the cement all of a sudden is produced cleaner. But the latter improvement is not visible in the LCA anymore, and thus not taken into account in decision making.

[6] Some scholars stress that from a theoretical perspective the allocation procedure, in which processes are split (i.c. option 2) is superior (HEIJUNGS, 1997: 80). This may be very true, but in a specific comparison it may still be preferable to compare *systems with multiple functions* (in fact option 1). Space constraints prevent a full analysis here, but it can be easily shown that splitting up processes, and involving both split-up parts afterwards in a comparison of systems with multiple functions, results actually in the system enlargement approach. In fact, not an allocation problem but a goal and scope question is at stake here: if a single-function comparison (waste destruction) or a multiple-function comparison (waste destruction, energy generation, etc.) is most appropriate. Once again, the authorities' argument to prefer a multiple-function comparison is in my view a valid one.

Table 2.2: Composition-dependent inventory table for cement kilns, rotary kilns and MSWIs

Component	Cement kiln		Rotary kiln			MSWI		
	Air	Clinker	Air	Water	Solids	Air	Water	Solids
Component related emissions: ton output per ton input (mass balance)								
As						5,17E-04	1,51E-05	9,99E-01
Cd						2,20E-03	3,12E-04	9,97E-01
Co						3,55E-04	0,00E+00	1,00E+00
Cr						2,27E-04	7,94E-05	1,00E+00
Cu						5,97E-05	8,21E-06	1,00E+00
Hg						1,83E-01	2,80E-05	8,17E-01
Mn						5,98E-05	0,00E+00	1,00E+00
Mo						0,00E+00	0,00E+00	1,00E+00
Ni	Confidential			Confidential		8,93E-04	5,71E-04	9,99E-01
Pb						7,45E-04	2,24E-05	9,99E-01
Sb						0,00E+00	0,00E+00	1,00E+00
Se						0,00E+00	0,00E+00	1,00E+00
Sn						0,00E+00	0,00E+00	1,00E+00
V						1,82E-05	0,00E+00	1,00E+00
Zn						7,57E-04	1,94E-05	9,99E-01
Cl						4,91E-04	2,30E-01	7,69E-01
F						2,96E-03	6,41E-03	9,91E-01
S (SO2/SO4)						9,07E-03	5,24E-02	2,93E+00
Process related emissions: ton emitted per MJ input								
NOx						2,50E-08		
NH4							2,52E-10	
CO2	7,81E-05		7,81E-05			7,81E-05		
COD							4,90E-10	
CO	Other: confidential		Other: confidential			1,30E-08		
TOC						1,50E-09		
Dioxins (TEQ)						5,00E-17		
PCB						2,50E-13		
HCB						9,00E-12		
Use of auxiliary materials as a function of composition in ton								
Lime/t Cl	0,00E+00					6,10E-01		
Lime/t S	0,00E+00			Confidential		1,36E+00		
NaOH/t Cl	0,00E+00					4,10E-01		
NaOH/t S	0,00E+00					9,10E-01		
By products: MJ energy production per MJ input								
El. en/MJ	0,00E+00		1,98E-01			2,16E-01		
Th. en/MJ	0,00E+00		1,48E-01			2,70E-01		

Note: Component related based on mass balance (fraction of input)
Process-related emissions based on energy content (ton emission per MJ)

2.2 Rotary kiln

A rotary kiln consists of a rotating tube in which hazardous waste is incinerated at high temperatures (over 1100 °C). A rotary kiln is capable of dealing with virtually all kinds of waste aggregations (→ *Table 2.1*). Dutch rotary kilns are equipped with a flue gas cleaning system consisting of an electrofilter, an acid scrubber and a caustic scrubber. Emissions take place to water and air.

Ash-containing waste contributes to the production of fly-ash and bottom ash, which is landfilled as hazardous waste. The caustic scrubber needs an input of caustic soda (NaOH) and limestone ($Ca(OH)_2$). Energy is recovered in the form of electricity and heat (cf. *Fig. 2.1*).

On the basis of various sources such as monitoring data and mass balances elaborated by AVR, and AVR's license applications and EIAs, a full input-output balance and energy balance of AVR's rotary kilns could be obtained (AVR, 1995, 1994a and 1994b). To calculate waste-specific inventory tables, the following approach was used:

a. The process-related emissions (such as PAHs, VOC, NO_x, dioxins, etc.), CO_2-emissions, and the electricity and heat generation were calculated per MJ waste input, and assumed to be proportional to this caloric value of waste[7, 8];
b. concerning the component-related emissions (such as metals, chlorine, and sulphur) it was assumed that components from a specific waste input would be distributed over the outputs (air, water and fly-ash/bottom ash) according to the component-specific mass balance derived for the kiln;
c. the total input of acidifying components into the kiln was known, and so the amount of caustic soda and lime-

stone used per unit of acidification potential could be calculated. This allowed for a waste specific allocation of caustic soda and lime, according to a waste's acidification potential;

d. the volume (mass) of fly-ash and bottom ash produced when a specific waste would be incinerated was assumed to be proportional to its ash content;

e. for emissions to soil, it is very uncertain how much metal will leach out from landfilled ashes on long term. We used an emission factor given by AOO (1995a) of 0.1%. The 0.1% is about an order of magnitude higher than values given by Finnveden et al. (1995) for the forseeable time frame.

To summarise, on the basis of a waste's caloric value, composition and ash content, the specific inventory table could be derived. We used heat production with gas and average electricity production for the Dutch grid as avoided processes. In the sensitivity analysis we included electricity generation with a coal power plant and heat production with an oil furnace as alternative avoided processes. Furthermore, for the rotary kiln emissions to air, next to the low actually measured levels we also used the maximum levels permitted in AVR's licence as a sensitivity analysis.

2.3 MSWI

Most Dutch MSWIs have a grid consisting of a number of rolls placed in a slope, over which the waste slowly rolls down. The incineration temperature is usually 800°C. They are equipped with electrofilters, flue gas cleaning (in most cases wet), a deNOx step and a charcoal filter. Emissions take place to water and air. Several residues are formed, ranging from fly-ash (30% re-used in asphalt), flue gas cleaning residue (all landfilled), and bottom ash (all re-used, mainly in road construction). The scrubbers need an input of caustic soda and limestone. Electricity and heat recovery takes place (cf. *Fig. 2.2*).

The methodology for calculating waste-specific emission profiles, and the choice of avoided processes, was the same as for rotary kilns. An LCA for the Dutch Municipal Solid Waste Management Plan, giving average data for Dutch MSWIs, formed the main data source (AOO, 1995a). Following AOO (1995a), it was assumed that 1% would leach out of the metals in waste flows that were recycled (i.e. part of the fly-ash, and all bottom ash)[9]. For landfilled flows this was, like for the rotary kiln, set on 0.1%.

[7] Process-related emissions do not depend on the composition of the waste input. Ideally, they are allocated to specific wastes according to the flue gas volume produced by a tonne of that waste. However, such data in general lack. Since the caloric value of a waste is often rather proportional to its flue gas volume production, this is often used as an alternative allocation basis (e.g. Sas, 1994).

[8] The kiln's own electricity use was unknown, and we estimated it on 500 MJ per tonne using data of AOO (1995a) for MSWIs. With hindsight, it would have been more consistent to assume that this energy use depends on the energy contents of the waste, since a reasonable part of this energy is used for flue gas cleaning, which in turn is often seen as proportional to its energy content. Yet, I decided here to stick to the calculations in the EIA, as accepted by the EIA commission.

[9] This is a simplification; average values for bottom ash range from 0.1 to 2% for different metals (AOO, 1995a)

MSWIs cannot deal with all hazardous waste types. However, it has to be noted that legal systems primarily define waste as hazardous if it is relatively dangerous for man and nature when illegally dumped. The definition does not imply automatically that treatment with specific technologies is necessary. For instance, (hazardous) waste oil will not behave very differently in an incinerator as an – as such harmless – plastic like polyethylene. On the basis of a 20-year experience, AVR and the authorities have derived hazardous waste acceptance criteria for AVR's MSWI (→ *Table 2.3*). The criteria for fluorine, chlorine, sulphur and PAHs are included since the necessary destruction efficiency at the relatively low temperature may not otherwise be reached. The other criteria (particularly for heavy metals) are of importance to control the bottom ash quality. A higher heavy metal input jeopardises the recycling of bottom ash, which would be very costly for MSWI-operators.

Table 2.3: Acceptance criteria of a Dutch MSWI for hazardous waste (in mg/kg)

Substance	Max. concentration	Substance	Max. concentration
S	10.000	PAH	1000
Cl	10.000	F, I, Br	Not present. (<0,01%)
Pb	750	Ag	10
Zn	1000	As	10
Cu	1000	Hg	0,25
Cd	10	Mo	75
Cr	75	Rh	10
Ni	75	Sb	10
Sn	100	Se	1,0
Co	10		

2.4 Cement kiln

A cement kiln consists of a tube of well over 150 meters in which alkalic raw materials are sintered at high temperatures (1400°C). Some kilns introduce the raw materials as a slurry; others in dry form. The first obviously needs a high amount of energy, which is usually provided by oil and several types of coal. High-ash coal that forms both an inorganic raw material and an energy source is sometimes used. There are usually no emissions to water. Flue gas cleaning is relatively simple (usually only an electrofilter). Electrofilter dust is reprocessed into the clinker, so no solid waste flows arise (NRW, 1995; Obourg, 1992 and 1995; AOO, 1995b; cf. *Fig. 2.3*). The energy bill of particularly wet cement kilns can be up to 25% of their turnover, which is an important incentive to use waste as fuel (Obourg, 1992).

Once again, via the same approach as used for rotary kilns, waste-specific inventory tables were calculated on the basis of a waste's caloric value and composition. (Confidential) basic data were obtained from the most important Belgium (wet) cement kiln that imports Dutch hazardous waste (Obourg, 1995). Using the assumption of AOO (1995a) mentioned earlier for re-use situations, it was assumed that 1% of these components would finally leach out of the clinker.

If a waste is used, the input of the same amount of MJ of a primary fuel with a specific composition is avoided, and hence the related emissions [10]. The precombustion chain of this fuel was also assumed to be avoided. Since the choice of the avoided fuel is crucial, we applied a sensitivity analysis in which various fuel types were included (coal with a high sulphur content, low sulphur content, gas oil, and crude)[11].

2.5 Combi-kiln

As for the combi-kiln, the data supply was poor. The company did not want to give data, and the license application and EIA of the firm did not allow for a waste-specific calculation of emission data (e.g. mass balances). We assumed that the performance could hardly be better than for the rotary kiln of the AVR, since that is built to deal with all possible wastes. From the information available, it became clear that the projected combi-kiln had no energy recovery system (AVB, 1995). We therefore modelled this kiln by using the data of AVR's rotary kiln, however without energy recovery (→ *Fig. 2.1-2.4*).

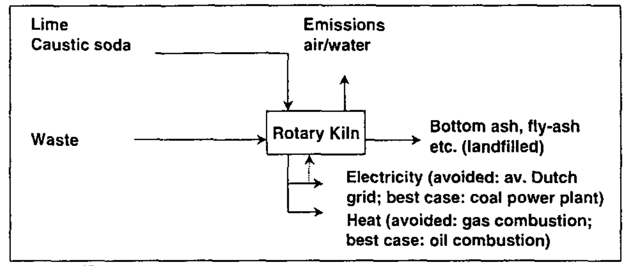


Fig. 2.1: The system related to waste treatment in a rotary kiln

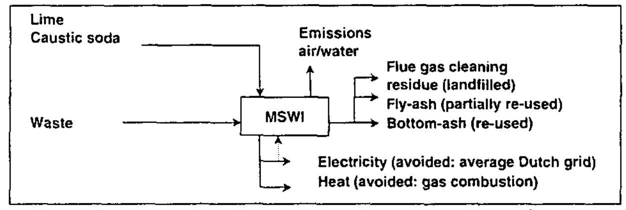


Fig. 2.2: The system related to waste treatment in a MSWI (grey: not included)

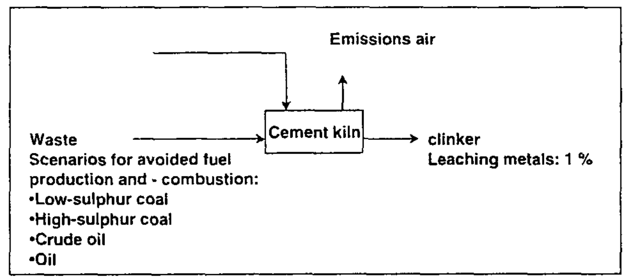


Fig. 2.3: The system related to waste treatment in a cement kiln (grey: not included)

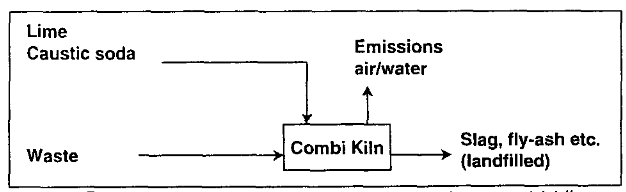


Fig. 2.4: The system related to waste treatment in a combi-kiln

3 Impact Assessment

3.1 Introduction

For the impact assessment methodology, we refer to **Part 1**. In brief, it concerned:

- The 1992 CML guide was used (HEIJUNGS et al., 1992), making some adaptions like including primary energy use and final waste as impact categories;
- normalisation took place on the basis of Dutch total scores for 1990;
- weighted scores were calculated with 3 methods: Distance to Target (DtT) related to Dutch policy goals for 2000, DtT without final waste, and all themes of equal weight.

Section 3.2 provides general results. Section 3.3 deals with a number of specific problems in the comparison: Allocation, the final fate of heavy metals, and the possible additional production of micropollutants when waste is incinerated in cement kilns.

3.2 A general review of results

Fig. 3.1 and 3.2 give results for two of the about 5 waste types for which the comparison has been performed. One waste type a) is a hypothetical, contaminant-free, high-caloric waste (e.g. spent solvent), and another waste type b) is assumed to be contaminated to the level of the acceptance criteria for MSWIs given in **Table 2.3**. Below, an analysis is given based on an underlying breakdown of theme scores (not given here due to space constraints). In general, the combi-kiln always scored worst due to its lack of energy recovery[12]. Therefore, the discussion concentrates on the other three options, including the sensitivity analysis with regard to the quality of flue gas cleaning (rotary kiln) and the avoided processes or fuels[13].

[10] In some cases, the situation is more complicated. Fuels like high-ash coal provide apart from energy also an inorganic raw material input. If this is replaced by a waste with a low ash content, the kiln needs additional inorganic raw material. Such influences are difficult to model, and we had to refrain from taking them into account. The uncertainties thus introduced may not be larger than we made already visible in our sensitivity analysis (see section 3). Inorganic raw material is extracted close to the kiln, and the energy use of such processes is relatively low compared to the overall process. The scarcity aspect probably is relevant, but is still poorly operationalised LCIA indicator systems.

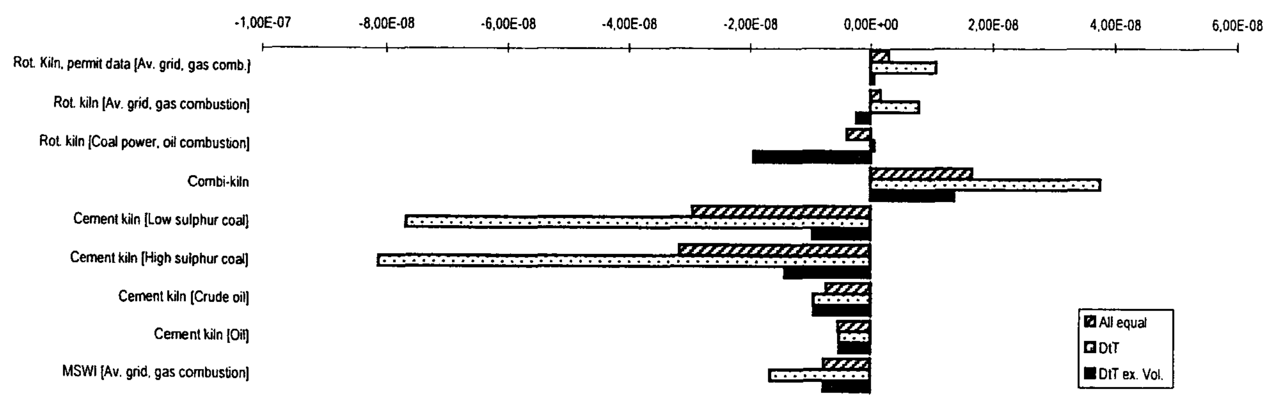
[11] We also did a sensitivity analysis in which we estimated the need for additional transport of the waste to Belgium. This appeared to be of minor importance and is not discussed here.

[12] With hindsight, this may look trivial. Yet, at the start of the LCA we had insufficient arguments to reject the combi kiln straight away. The initiator of the combi kiln may have accepted that his kiln would score worse than a rotary kiln, but not that it was worse than e.g. a cement kiln. Hence, he could try to claim that his proposed kiln was in any case better than export to presumably 'dirty' cement kilns.

[13] We did not vary the avoided processes for the MSWIs; this would simply result in similar changes as shown for the rotary kiln. In the underlying report we also included a sensitivity analysis in which we assumed that high-caloric waste was essential for rotary kilns to incinerate low-caloric waste, i.e. that using of high-caloric waste in cement kilns would force rotary kilns to buy primary fuel. This appeared to have no fundamental effect on the analysis, which can in part be explained as follows. High-caloric hazardous waste may, particularly with regard to their sulphur content, be of better quality as the regular fuel of cement kilns. Then it is simply more effective that a cement kiln (with its limited flue gas cleaning) burns 'clean' waste and the rotary kiln (with its extensive flue gas cleaning) burns heavy oil.

Table 3.1: Normalised scores for incineration of waste according to the acceptation limits of a MSWI, 15 MJ/kg, 10% ash

Theme and DtT Factor	Humtox	Ecotox	GWP	ODP	POCP	Acidif.	Eutrophic	Volume	Energy	Weighted scores		
Technology [avoided processes]	**1,7**	**1,7**	**1,2**	**35**	**2,3**	**2,6**	**2,8**	**3,1**	**1,02**	**All equal**	**DtT**	**DtT ex. Vol.**
Rot. Kiln, permit data [Av. grid, gas comb.]	2,28E-10	4,60E-10	2,30E-09	0	-2,35E-10	3,28E-10	1,04E-10	3,30E-09	-3,08E-09	2,94E-09	1,08E-08	6,07E-10
Rot. kiln [Av. grid, gas combustion]	-3,41E-10	4,60E-10	2,30E-09	0	-2,35E-10	-4,04E-10	1,04E-10	3,30E-09	-3,08E-09	1,64E-09	7,95E-09	-2,26E-09
Rot. kiln [Coal power, oil combustion]	-3,63E-09	3,75E-10	1,38E-09	0	-9,40E-10	-3,40E-09	-2,41E-11	6,44E-09	-3,76E-09	-3,93E-09	5,51E-10	-1,94E-08
Combi-kiln	1,27E-09	4,60E-10	5,30E-09	0	2,43E-10	1,27E-09	2,60E-10	7,69E-09	5,61E-10	1,66E-08	3,75E-08	1,37E-08
Cement kiln [Low sulphur coal]	3,50E-10	0,00E+00	-9,22E-10	0	-1,79E-09	4,10E-10	-1,89E-11	-2,16E-08	-5,84E-09	-2,94E-08	-7,65E-08	-9,57E-09
Cement kiln [High sulphur coal]	-6,90E-10	0,00E+00	-9,22E-10	0	-1,79E-09	-6,47E-10	-1,89E-11	-2,16E-08	-5,84E-09	-3,15E-08	-8,10E-08	-1,41E-08
Cement kiln [Crude oil]	-6,07E-10	-3,17E-10	-1,97E-10	0	-3,53E-10	-6,35E-10	-2,23E-11	-1,40E-11	-5,52E-09	-7,35E-09	-9,47E-09	-9,42E-09
Cement kiln [Oil]	3,86E-10	-3,17E-10	-1,97E-10	0	-3,53E-10	3,66E-10	-2,23E-11	-1,40E-11	-5,52E-09	-5,35E-09	-5,17E-09	-5,13E-09
MSWI [Av. grid, gas combustion]	-1,01E-09	9,35E-11	1,63E-09	0	-1,23E-10	-1,27E-09	-1,03E-10	-2,84E-09	-4,05E-09	-7,76E-09	-1,66E-08	-7,76E-09



Figures and tables support the main text. Underlying assumptions are decisive in the interpretation.
Conclusions shall therefore not be based on the tables and figures but on the accompanying text.

Fig. 3.1: Weighted scores for incineration of waste according to the acceptation limits of a MSWI

Concerning human and aquatic ecotoxicology, the cement kiln tends to score rather good if rather clean waste is used as a secondary fuel. This is logical, since in that case the avoided fuel simply contains more contaminants. The rotary kiln scores relatively good when a contaminated waste like type b) is incinerated, which is rather logical since its flue gas cleaning is relatively good. Yet, in view of the problems with impact assessment of toxic releases (TUKKER, 1998a), the value of these scores is highly uncertain. For instance, SO_2 and NO_x dominate human toxicity since this study still had to use the 1992 CML guide that neglected the fate step in toxicity impact assessment.

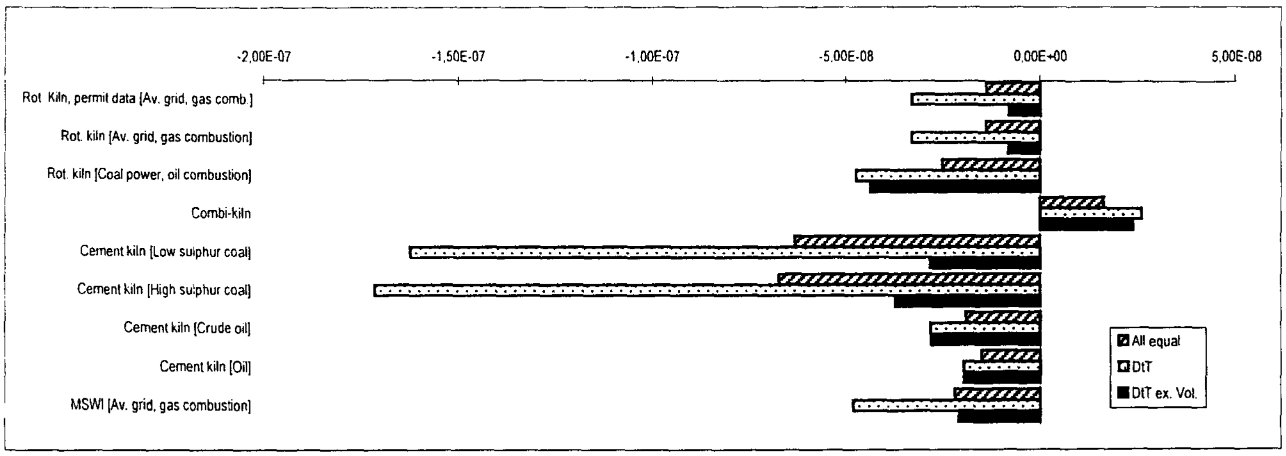
The greenhouse effect is correlated with the total energy use. The cement kiln scores relatively good since it recovers 100% energy. On waste volume, the rotary kiln scores rather poorly: Residues are landfilled, where the MSWI and cement kiln produce recyclable residues or no residues at all. Avoided electricity production, as that derived from coal power plants, leads to avoided landfill: Coal extraction results in a high production of mine tailings. Due to its high energy recovery, the MSWI scores better here too. Similarly, the cement kiln scores extremely well if coal use is assumed to be avoided.

Smog formation, acidification and eutrophication are, in large, caused by process-related emissions (except for SO_2). If a cement kiln uses a waste with a similar sulphur content instead of fuel, the waste-related and avoided emissions from the kiln itself are in balance. The score of the cement kiln is thus largely determined by the precombustion chains related to the avoided fuel use; for acidification, the difference in sulphur content of the fuel and the waste plays a role as well. For the rotary kiln and MSWI, the scores of the incineration processes themselves are very low due to good flue gas cleaning, and the avoided electricity production and heat production dominate. Since the modern Dutch MSWIs recover energy somewhat more efficiently than the rotary kiln at AVR, the MSWI scores better in comparison.

Concerning the sensitivity analysis, the differences in flue gas cleaning quality for rotary kilns only affect scores on human toxicity and acidification in cases where contaminated waste is incinerated. Choices for different avoided

Table 3.2: Normalised scores for incineration of uncontaminated organic waste, 30 MJ/kg, 0% ash

Theme and DtT Factor	Humtox	Ecotox	GWP	ODP	POCP	Acidif.	Eutrophic.	Volume	Energy	Weighted scores		
Technology [avoided processes]	1,7	1,7	1,2	35	2,3	2,6	2,8	3,1	1,02	**All equal**	**DtT**	**DtT ex. Vol.**
Rot. Kiln, permit data [Av. grid, gas comb.]	-1,16E-09	5,59E-13	4,00E-09	0	-6,06E-10	-1,18E-09	1,76E-10	-8,06E-09	-6,82E-09	-1,36E-08	-3,31E-08	-8,09E-09
Rot. kiln [Av. grid, gas combustion]	-1,16E-09	5,59E-13	4,00E-09	0	-6,06E-10	-1,18E-09	1,76E-10	-8,06E-09	-6,82E-09	-1,36E-08	-3,31E-08	-8,09E-09
Rot. kiln [Coal power, oil combustion]	-8,03E-09	-1,76E-10	2,04E-09	0	-2,01E-09	-7,42E-09	-9,50E-11	-1,14E-09	-8,33E-09	-2,50E-08	-4,74E-08	-4,39E-08
Combi-kiln	2,07E-09	5,59E-13	1,00E-08	0	3,51E-10	2,18E-09	4,89E-10	7,38E-10	4,57E-10	1,63E-08	2,61E-08	2,38E-08
Cement kiln [Low sulphur coal]	-1,47E-09	0,00E+00	-1,84E-09	0	-3,58E-09	-1,29E-09	-3,77E-11	-4,32E-08	-1,17E-08	-6,31E-08	-1,62E-07	-2,83E-08
Cement kiln [High sulphur coal]	-3,55E-09	0,00E+00	-1,84E-09	0	-3,58E-09	-3,40E-09	-3,77E-11	-4,32E-08	-1,17E-08	-6,73E-08	-1,71E-07	-3,73E-08
Cement kiln [Crude oil]	-3,39E-09	-6,33E-10	-3,94E-10	0	-7,07E-10	-3,38E-09	-4,46E-11	-2,80E-11	-1,10E-08	-1,90E-08	-2,81E-08	-2,80E-08
Cement kiln [Oil]	-1,40E-09	-6,33E-10	-3,94E-10	0	-7,07E-10	-1,37E-09	-4,46E-11	-2,80E-11	-1,10E-08	-1,50E-08	-1,95E-08	-1,94E-08
MSWI [Av. grid, gas combustion]	-2,93E-09	1,14E-12	2,59E-09	0	-4,10E-10	-3,19E-09	-2,39E-10	-8,83E-09	-8,85E-09	-2,19E-08	-4,82E-08	-2,08E-08



Figures and tables support the main text. Underlying assumptions are decisive in the interpretation.
Conclusions shall therefore not be based on the tables and figures but on the accompanying text.

Fig. 3.2: Weighted scores for incineration of uncontaminated organic waste, 30 MJ/kg, 0% ash

processes have large influences. For instance, if electricity production with coal power plants and energy production with oil furnaces are avoided, this improves the scores of the rotary kiln greatly. On the other hand, if a relatively clean oil rather than a high-sulphur coal is avoided at cement kilns, the score of cement kilns worsens rapidly.

3.3 A specific analysis of three crucial elements in the analysis

3.3.1 Introduction

The weighted scores in Fig. 3.1 and 3.2 already indicate that speaking out unambiguous preferences is difficult; only the combi-kiln can clearly be rejected. While performing the LCA, we had already learned by a process of 'stakeholder deliberation' (informal talks, studying interviews and literature, and own deduction) that stakeholders had highly diverging opinions on the following issues:

- The formation of toxic micropollutants in stack gases, such as dioxins, by cement kilns;
- the final fate of heavy metals if very contaminated waste would be incinerated;
- how to deal with allocation.

For the comparison of rotary kilns and MSWIs, these points were less relevant. The acceptance criteria given in Table 2.3 would prevent the acceptance of highly metal-containing waste in MSWIs; both have rather similar flue gas cleaning; and finally, the by-products are similar. Hence, these questions are mainly important for comparing the cement kiln, on the one hand, with the rotary kiln and MSWI on the other.

3.3.2 Toxic substances in stack gases

Cement kilns lack an extensive flue gas cleaning. Environmentalists appeared to fear that waste incineration in cement kilns could lead to the formation of toxic micropollutants and particles of incomplete combustion (PICs), such as dioxins. Cement kiln operators disagree, pointing at the high temperatures and residence times (some 20 seconds at 1400°C, where for rotary kilns this is about 2 seconds and 1100°C). However, literature is simply controversial

about this issue. Some literature, for example, suggests that there is hardly a rise in dioxin emissions (DEMPSEY and OPPELT, 1993; BENESTADT, 1995; SCHREIBER, 1995), while other literature provides reason for concern (HELLBERG, 1995; DE FRÉ and WEVERS, 1995; Greenpeace, 1995). Despite several requests, we never obtained results of a comprehensive trial burn programme under the various conditions that can occur in cement production[14].

This uncertainty can easily be tackled by good monitoring, probably costing a fraction of the income that cement kilns generate by incinerating hazardous waste. The Precautionary Principle unambiguously states that such easy to tackle uncertainties shall be avoided, particularly since additional emissions of PICs can have severe consequences (cf. UNCED, 1992). We concluded that this concern could not be solved within the context of our LCA. The only solution is to demand trial burns and extensive monitoring before allowing cement kilns to incinerate waste with a different composition as their regular fuel.

3.3.3 Final fate of metals

A second controversial point was that for cement kilns nearly all (additional) heavy metals in the input end up in the cement, for MSWIs largely in re-used ashes, and for rotary kilns in ashes landfilled on a controlled landfill. Due to the large uncertainties in leaching emission factors and toxicity equivalency factors, it is very difficult to obtain a commonly accepted answer concerning which route will minimise the related terrestrial ecotoxicological effects with LCA (TUKKER and WRISBERG, 1998b).

Intuitive preferences (e.g. for 'safe' landfill) can easily be countered. Dutch legislation demands stringent soil protection measures for all routes. Over 100 years, building materials used in construction and landfills may leach out to such an extent that only a marginal enrichment (i.e. 1%) occurs to the metal concentration in the first meter of underlying soil. Cement, re-used MSWI-slag and landfilled rotary kiln slag all have to meet this standard, which is likely to prevent any significant actual effect on medium term. Indeed, there are even investigations if heavy metal containing waste can be re-used under the above criteria by immobilising it with... cement ! Furthermore, maybe due to dilution effects, leaching tests have shown no or hardly any differences in leaching behaviour of cement made with or without a waste input into cement kilns (KARSTENSEN, 1994).

This implied an important knowledge gap. Specifically for waste with high metal contents, the (unknown) effects related to the leaching of metals could actually be more relevant than the topics for which calculations had been made (EIA Commission, 1996). Discussions with the EIA Commission inspired us to try to quantify this concentration boundary. **Table 3.1** and **3.2** indicate that normalised theme scores of about 5.00 E-09 can not be called negligible anymore. Hence, the knowledge gap would be relevant for waste containing heavy metal concentrations that could lead to such high ecotoxicity scores[15] under conservative assumptions.

As stated before, leaching tests suggest that a maximum of 1% of the heavy metals may leach out under regular landfill or re-use conditions. We assumed that this 1% could either contribute to aquatic or terrestrial ecotoxicity. With the available equivalency factors, it is possible for a certain metal to calculate at which concentration in waste, if 1% leaches out, a normalised score on aquatic or terrestrial ecotoxicity can be reached of 5.00 E-09. This calculation was made after the EIA was published (TUKKER, 1996b). Therefore, apart from factors from the 1992 CML guide, we could also use the then published USES-based equivalency factors of Guinée et al. (1996)[16]. **Table 3.3** (*p. 349*) reviews the calculations. They suggest that the knowledge gap for Cd and Hg can become important at concentrations of roughly 0.001 to 0.01% and for other metals between roughly 0.1 to 1%. It must be stressed that these values themselves are still very uncertain. With regard to the (large) uncertainties in the equivalency factors (cf. TUKKER, 1998a), one may hope that at least one of the often quite diverging four calculations per metal (two topics, two sets of equivalency factors) results in a realistic worst case. Yet, all calculations use the same estimated emission factor for leaching (1%). Some authors think this is still far to optimistic (cf. HELLWEG and HUNGERBÜHLER, 1999a and HELLWEG, 1999b)[17]. If they are right, the concentration boundaries given above could easily be an order of magnitude lower.

3.3.4 The influence of an alternative allocation method

For cement kilns and rotary kilns, **Fig. 3.3** shows the results when an alternative allocation system is applied. The waste type is the same as used in **Table 3.1** and **Fig. 3.1**; the comparison at stake is between a cement kiln and a rotary kiln. The MSWI is not shown since the relevant sensitivities related to allocation are the same as for the rotary kiln.

In **Table 3.4** and **Fig. 3.3**, the rotary kiln and cement kilns are seen as tools with 3 or 2 different functions, respectively: 'Waste destruction', 'electricity production' and 'heat generation' for the rotary kiln and 'waste destruction', 'heat supply' and 'inorganic material supply (if ash-containing waste is used)' for the cement kiln. Interventions are allocated to each function according to economic value resulting in a 'net' emission for the waste destruction function. A sensitivity analysis is included for different price levels, reflected by the different percentages allocated to the function

[14] We received only one report for one, rather uncontaminated waste, under unspecified conditions. At the same time, Dutch electricity plants have to do comprehensive tests for any new (in general non-hazardous) waste they want to incinerate.

[15] We stress that the boundary only indicates where the *knowledge gap* can become decisive in the comparison between rotary kilns, MSWIs and cement kilns. It does *not* mean that above the boundary controlled landfill is the best option; merely that the comparison may start to hing on the way how one wants to deal with the heavy metals in the waste.

[16] Dutch normalisation values for these USES-based factors were not yet available. We estimated them on the basis of an extrapolation of data for Sweden given by Tukker and Kleijn (1996c).

[17] Indeed, total availability tests on bottom ash with a liquid/solid ratio of 100 in an acid environment (pH = 4) result for Zn and Cd in losses of several dozen percent (AOO, 1995a: 37). One can debate, however, if such circumstances can be seen as a realistic worst-case for landfill conditions or material bound in cement.

Table 3.3: Metal concentrations with significant scores if 1% leaches out from 1 ton waste

	Theme	Significant score (a)	Normalisation value (b)		Equivalency factor (c)		Correction units	Factor 100	Concentration (ton/ton)	Range
As	ECA	5,00E-09	9,00E+12	m3	0,2	m3/mg	1,00E-09	100	2,25E-02	
	ECT	5,00E-09	1,26E+13	kg	3,6	kg/mg	1,00E-09	100	1,75E-03	0,2 to 2 %
	AETP	5,00E-09	1,62E+09	kg	1,90E+02	kg/kg	1,00E-03	100	4,26E-03	
	TETP	5,00E-09	4,98E+13	kg	2,00E+05	kg/kg	1,00E-03	100	1,25E-01	
Cd	ECA	5,00E-09	9,00E+12	m3	200	m3/mg	1,00E-09	100	2,25E-05	
	ECT	5,00E-09	1,26E+13	kg	13	kg/mg	1,00E-09	100	4,85E-04	0,002 to 0,05 %
	AETP	5,00E-09	1,62E+09	kg	4,50E+03	kg/kg	1,00E-03	100	1,80E-04	
	TETP	5,00E-09	4,98E+13	kg	3,40E+08	kg/kg	1,00E-03	100	7,32E-05	
Co	ECA	5,00E-09	9,00E+12	m3		m3/mg	1,00E-09	100		
	ECT	5,00E-09	1,26E+13	kg	0,42	kg/mg	1,00E-09	100	1,50E-02	1 to 50 %
	AETP	5,00E-09	1,62E+09	kg	88	kg/kg	1,00E-03	100	9,20E-03	
	TETP	5,00E-09	4,98E+13	kg	4,50E+04	kg/kg	1,00E-03	100	5,53E-01	
Cr (III)	ECA	5,00E-09	9,00E+12	m3	1	m3/mg	1,00E-09	100	4,50E-03	
	ECT	5,00E-09	1,26E+13	kg	0,42	kg/mg	1,00E-09	100	1,50E-02	0,5 to 4 %
	AETP	5,00E-09	1,62E+09	kg	84	kg/kg	1,00E-03	100	9,64E-03	
	TETP	5,00E-09	4,98E+13	kg	6,00E+05	kg/kg	1,00E-03	100	4,15E-02	
Cu	ECA	5,00E-09	9,00E+12	m3	2	m3/mg	1,00E-09	100	2,25E-03	
	ECT	5,00E-09	1,26E+13	kg	0,77	kg/mg	1,00E-09	100	8,18E-03	0,2 to 1 %
	AETP	5,00E-09	1,62E+09	kg	96	kg/kg	1,00E-03	100	8,44E-03	
	TETP	5,00E-09	4,98E+13	kg	2,40E+06	kg/kg	1,00E-03	100	1,04E-02	
Hg	ECA	5,00E-09	9,00E+12	m3	500	m3/mg	1,00E-09	100	9,00E-06	
	ECT	5,00E-09	1,26E+13	kg	29	kg/mg	1,00E-09	100	2,17E-04	0,0006 to 0,1 %
	AETP	5,00E-09	1,62E+09	kg	1,30E+05	kg/kg	1,00E-03	100	6,23E-06	
	TETP	5,00E-09	4,98E+13	kg	1,70E+07	kg/kg	1,00E-03	100	1,46E-03	
Ni	ECA	5,00E-09	9,00E+12	m3	0,33	m3/mg	1,00E-09	100	1,36E-02	
	ECT	5,00E-09	1,26E+13	kg	1,7	kg/mg	1,00E-09	100	3,71E-03	0,03 to 5 %
	AETP	5,00E-09	1,62E+09	kg	2,70E+03	kg/kg	1,00E-03	100	3,00E-04	
	TETP	5,00E-09	4,98E+13	kg	5,20E+05	kg/kg	1,00E-03	100	4,79E-02	
Pb	ECA	5,00E-09	9,00E+12	m3	2	m3/mg	1,00E-09	100	2,25E-03	
	ECT	5,00E-09	1,26E+13	kg	0,43	kg/mg	1,00E-09	100	1,47E-02	0,2 to 86%
	AETP	5,00E-09	1,62E+09	kg	40	kg/kg	1,00E-03	100	2,03E-02	
	TETP	5,00E-09	4,98E+13	kg	2,90E+04	kg/kg	1,00E-03	100	8,59E-01	
V	ECA	5,00E-09	9,00E+12	m3		m3/mg	1,00E-09	100		
	ECT	5,00E-09	1,26E+13	kg		kg/mg	1,00E-09	100		
	AETP	5,00E-09	1,62E+09	kg	3,80E+02	kg/kg	1,00E-03	100	2,13E-03	0,2 to 2 %
	TETP	5,00E-09	4,98E+13	kg	1,20E+06	kg/kg	1,00E-03	100	2,08E-02	
Zn	ECA	5,00E-09	9,00E+12	m3	0,38	m3/mg	1,00E-09	100	1,18E-02	
	ECT	5,00E-09	1,26E+13	kg	2,6	kg/mg	1,00E-09	100	2,42E-03	0,2 to 2 %
	AETP	5,00E-09	1,62E+09	kg	86	kg/kg	1,00E-03	100	9,42E-03	
	TETP	5,00E-09	4,98E+13	kg	1,80E+06	kg/kg	1,00E-03	100	1,38E-02	

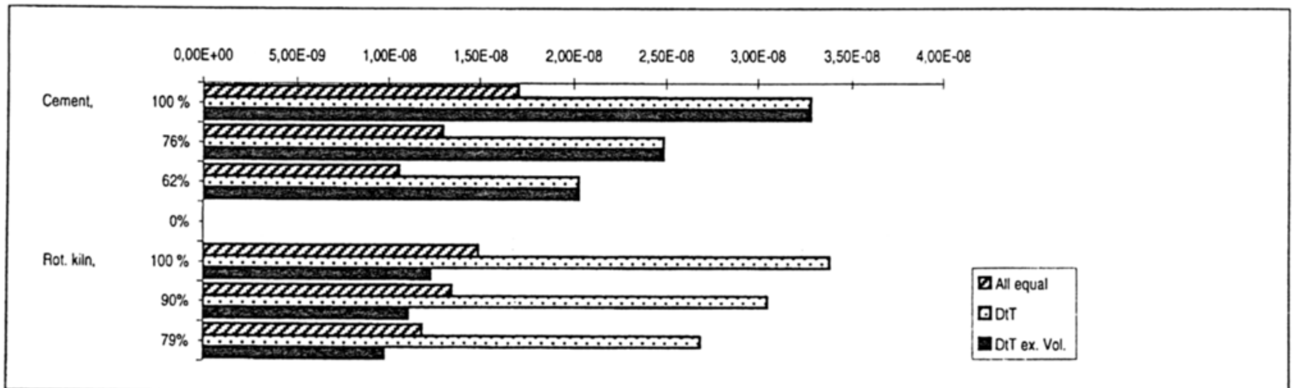
Explanation: ECA (Ecotoxicity, Aquatic) and ECT (Ecotoxicity, Terrestrial): impact categories as defined by Heijungs et al. (1992). AETP (Aquatic Ecotoxicity Potential) and TETP (Terrestrial Ecotoxicity Potential): impact categories as defined by Guinée et al. (1996). ECA and ECT need a correction of 1E-09 since equivalencyfactors are in m^3/mg emission and the concentration is calculated in ton/ton waste. For AETP and TETP the difference between kg and ton has to be bridged. Factor 100 due to 1 % leaching, thus 100 times more in waste. Concentration is calculated by 100* correction*a*b/c.

'waste destruction' in **Table 3.4** (see TUKKER, 1996a: B74)[18]. Since cement kilns generally have a lower quality flue gas cleaning system, as shown in **Fig. 3.3**, their allocated emissions to waste are in most cases higher.

[18] In theory, one could also see the cement kiln as a new chain, in which the waste is applied via open loop recycling. In such a view the waste is seen as a fuel, and all related emissions are allocated to the production of cement. The emissions allocated to the waste are zero: it is incinerated 'for free'. This is indicated with the 0% bar in the figure and table.

Table 3.4: Normalised scores, functional allocation, acc. limits MSWI, 15 MJ/kg, 10% ash (% allocated to 'waste destruction')

		Humtox	Ecotox	GWP	Ozon	Smog	Acidif.	Eutroph.	Volume	Energy	Weighted scores		
DtT-factor		1,7	1,7	1,2	35,3	2,3	2,6	2,8	3,1	1,02	All equal	DtT	DtT ex. Vol.
Cement,	100 %	4,78E-09	0,00E+00	4,80E-09	0	2,37E-09	4,45E-09	6,70E-10	0,00E+00	0,00E+00	1,71E-08	3,28E-08	3,28E-08
	76%	3,62E-09	0,00E+00	3,64E-09	0	1,80E-09	3,37E-09	5,08E-10	0,00E+00	0,00E+00	1,29E-08	2,48E-08	2,48E-08
	62%	2,95E-09	0,00E+00	2,96E-09	0	1,46E-09	2,75E-09	4,14E-10	0,00E+00	0,00E+00	1,05E-08	2,02E-08	2,02E-08
	0%	0,00E+00	0,00E+00	0,00E+00	0	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Rot. kiln,	100 %	1,04E-09	4,60E-10	4,89E-09	0	1,71E-10	1,02E-09	2,37E-10	6,95E-09	1,04E-10	1,49E-08	3,38E-08	1,22E-08
	90%	9,34E-10	4,15E-10	4,41E-09	0	1,54E-10	9,24E-10	2,13E-10	6,27E-09	9,34E-11	1,34E-08	3,05E-08	1,10E-08
	79%	8,21E-10	3,65E-10	3,88E-09	0	1,35E-10	8,12E-10	1,88E-10	5,51E-09	8,21E-11	1,18E-08	2,68E-08	9,70E-09



Note: the percentage indicate which percentage of a kiln's total interventions is allocated to the function 'waste destruction'

Fig. 3.3: Weighted scores, functional allocation (% allocated to 'waste destruction')

Hence, functional allocation tends to be advantageous for rotary kiln incineration, whereas system enlargement tends to be favourable for cement kilns. As we explained in section 2.1, however, since the latter results in the most complete insight in the total changes of the societal production system as a result of decision making on waste management, we feel system enlargement can be defended very well.

4 Conclusions

The conclusion about the comparison between the rotary kiln, MSWI, cement kiln and combi-kiln are as follows:

The combi kiln is a kiln without energy recovery. Our analysis clearly shows that it has no added value in the Dutch hazardous waste management system.

The differences in theme scores between the rotary kiln and MSWI appear to be small. However, we feel it is possible to speak out a preference. All differences are in favour of the MSWI and, more important, they can be explained with clear technical reasons. First, most Dutch MSWIs have been constructed very recently, and have on the average better electric and thermic energy recoveries than the existing rotary kiln. Hence, the advantage on the topics of energy use and global warming are structural. The waste volume is relatively low since slags are re-used, in contrast to the rotary kiln. If the acceptance criteria given in **Table 2.3** are met, one may assume that the problem of the leaching of metals from the re-use application will be relatively unimportant. Furthermore, the flue gas cleaning systems are quite comparable, so that the avoided emissions related to energy recovery are once again decisive. To summarise, under the precondition that the acceptance criteria in **Table 2.3** are met, it is likely that an MSWI is preferable over a rotary kiln. In other cases, the lower combustion temperatures may lead to additional PICs and the leaching of metals from re-used residues may become problematic.

Concerning the cement kiln, a question mark is the fate of heavy metals. It is impossible to speak out a preference between landfill with rotary kiln residues, or a slight enrichment of cement which leads to no detectable, additional leaching. At low metal concentrations (e.g. in the range of those in primary materials for the cement kiln), this knowledge gap does not seem to be too problematic. Probably the major problem is the uncertainty about PICs. We therefore make any conclusion about cement kilns conditional: *Only* if measurements under all possible operation conditions have shown that no additional PICs will be formed, can the incineration of waste with a different composition from the regular fuel be seen as an option.

If the cement kiln stands out in such comprehensive trial burns, our analysis does not allow the conclusion that a rotary kiln should be preferred. In case of an allocation by system enlargement which can be defended very well, the cement kiln tends to have even better scores. **Table 3.2** and **Fig. 3.2** show that the rotary kiln only scores better if 'dirty' avoided processes are used for the rotary kiln and 'clean' avoided fuels for the cement kiln. Hence, no preference is indicated here since the choice of the allocation system can make the one or the other score better. This cautious conclusion was already bad enough for the Dutch rotary kiln operator. They had thought they were by far the best performers, which even had been stated by the Dutch environmental minister in the Lower House half a year before the EIA was started.

Therefore, this case is a good example how an LCA perspective can result in new, surprising views, with important consequences for the market perspectives and – protection that rotary kilns had. Indeed, in the meantime, jurisprudence of the EU Court of Justice left Dutch authorities no choice but to allow free transboundary waste transport for re-use, including cement kiln incineration – with, as a consequence, dramatic market losses for AVR. Finally, it can be noted that the problems that prevented us to speak out clear-cut preferences – production of PICs, the final fate of heavy metals, and the preferred way of allocation - are not or hardly solvable within the framework of LCA.

5 References

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